UNIVERSITY OF EXETER

EPSRC Centre for Doctoral Training in Metamaterials

XM²

Theory of Linear Spin Wave Emission from a Bloch Domain Wall

N.J. Whitehead[1], T.G. Philbin[1], S.A.R. Horsley[1], A.N. Kuchko[2], V.V. Kruglyak[1]

[1]Department of Physics & Astronomy, University of Exeter, Stocker Road, Exeter, UK, EX4 4QL

[2]Donetsk National University, 24 Universitetskaya Street, Donetsk, 83001, Ukraine

Abstract. An analytical theory of exchange spin wave emission from a Bloch domain wall in a thin film is presented. We model a ferromagnet with antiparallel domains aligned along the (in-plane) easy-axis, where the hard axis points out of the film plane. When excited by a continuous, harmonic external magnetic field oriented orthogonal to the domain wall, plane spin waves are emitted above a threshold frequency. Crucially, the spin waves are emitted as a result of a linear excitation, not due to domain wall motion.

Introduction

Exchange spin waves (SWs) have great potential as **information carriers** on the nanoscale, due to their **short wavelengths** and **isotropic, quadratic dispersion** [1,2].

The wavelengths of SWs generated via **electrical antennas** or point contacts are **limited** by the **size** of the device [2].

Recent work [3-6] has demonstrated that **domain walls can generate SWs,** although **the mechanism is unclear**.

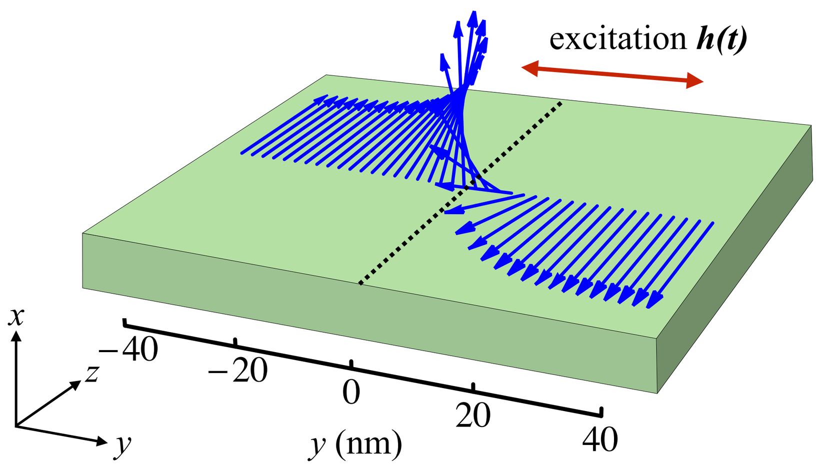


Fig.1: The studied system. The dotted line indicates the domain wall centre, and blue arrows represent the static magnetisation configuration.

We use **analytical theory** to explain this phenomena for **exchange SWs**.

We model an infinitely wide **thin film**, with a **pinned Bloch domain wall** separating two antiparallel domains, shown in Fig.1. Note the film lies in the **y-z plane**.

Background Theory

Excitation of the sample via an in-plane, time-varying magnetic field $\mathbf{h}(t)$ induces **precession** of the magnetisation $\mathbf{M}$, described by the **Landau-Lifshitz equation** without damping:

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma[\mathbf{M}\times\mathbf{H}_{eff}]$$

The effective field $\mathbf{H}_{eff}$ is the functional derivative of the free energy density W:

$$W = \underbrace{\frac{\alpha}{2}\left(\frac{\partial \mathbf{M}}{\partial y}\right)^2}_{\text{Exchange}} - \underbrace{\frac{\beta_\parallel}{2}(\mathbf{M}\cdot\hat{\mathbf{z}})^2}_{\text{In-Plane Anisotropy}} + \underbrace{\frac{\beta_\perp}{2}(\mathbf{M}\cdot\hat{\mathbf{x}})^2}_{\text{Out-of-Plane Anisotropy}} - \underbrace{\mathbf{h}\cdot\mathbf{M}}_{\text{Excitation}}$$

Minimising W in spherical coord's leads to the domain wall profile (Fig.2) - a function of *y* and the domain wall width λ_B:

$$\theta = 2\arctan\left[\exp\left(\frac{y}{\lambda_B}\right)\right]$$

We **rotate the frame of reference**, as shown in Fig.3, to follow the static magnetisation $\mathbf{M}_0$.

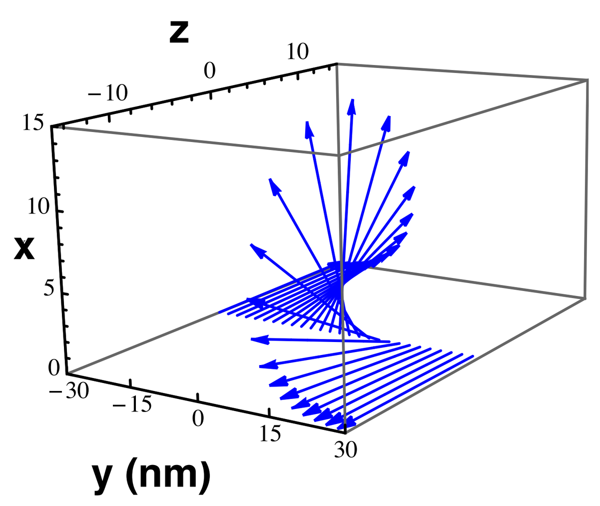


Fig.2: Static magnetisation $\mathbf{M}_0$ with $\lambda_B \approx$ 6nm. NB: The length of $\mathbf{M}_0$ is arbitrarily sized for clarity.

We then **linearise** the Landau-Lifshitz equation and solve for $\tilde{\mathbf{m}}'_\beta$, the excitation of magnetisation due to the domain wall.

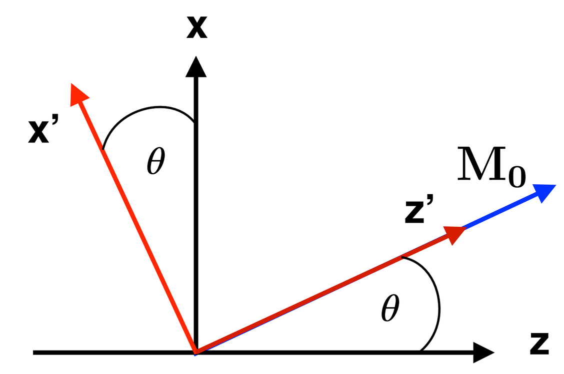
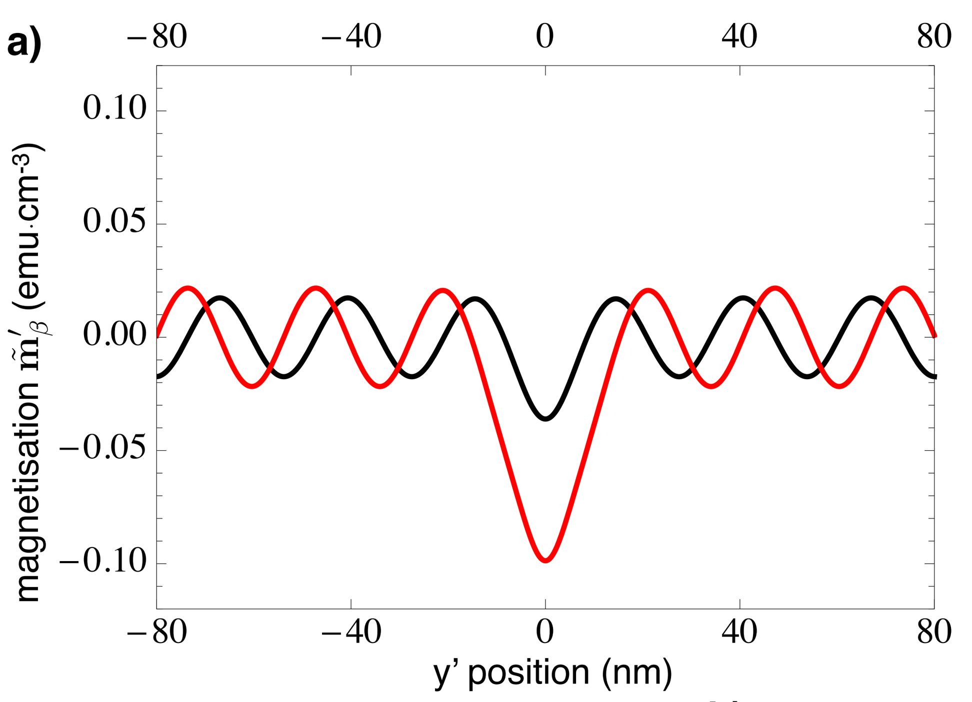


Fig.3: Rotated (primed) frame. The **z'** axis always follows $\mathbf{M}_0$, and **y = y'**.

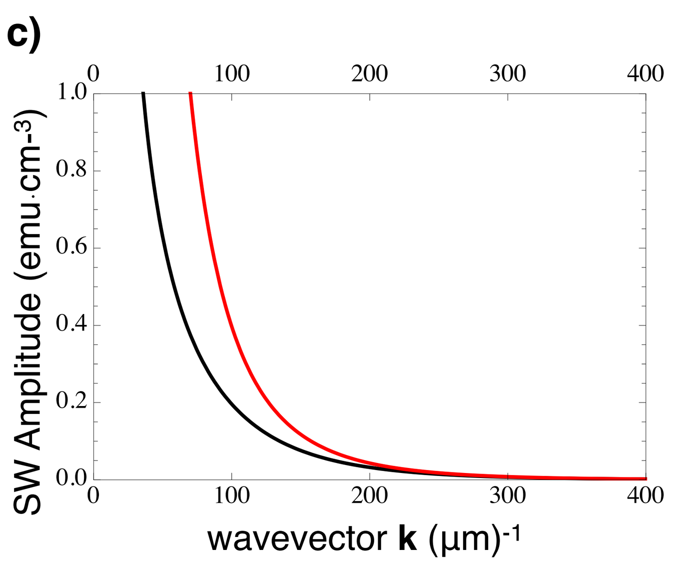
Results & Discussion

- **SWs emitted** for frequency: $\omega > \gamma M_0\sqrt{\beta_\parallel(\beta_\parallel+\beta_\perp)}$ (Fig.4a, 4b).
- Amplitude and wavelength (Fig.4c) determined by $\mathbf{h}(t)$.

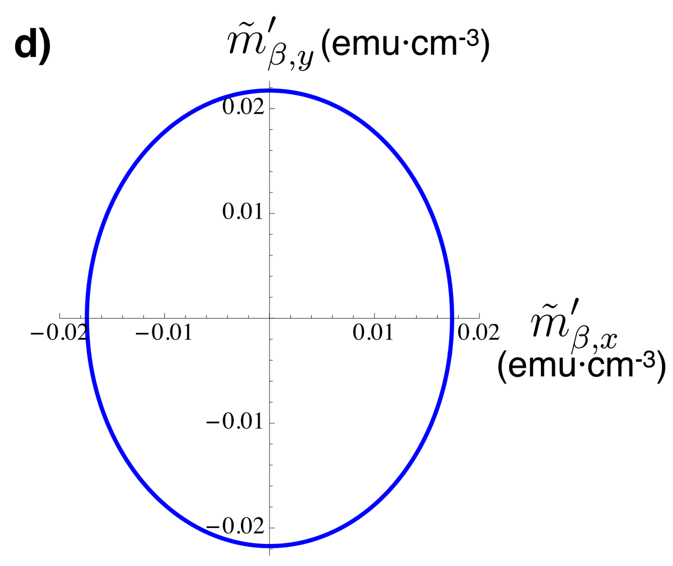
a)



c)



d)



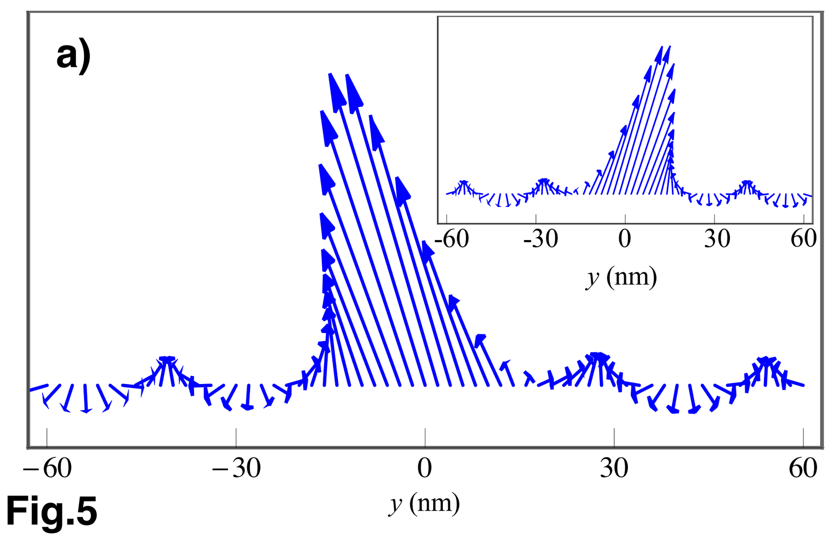
b)

Fig.4
a) x' component (black) and y' component (red) of $\tilde{\mathbf{m}}'_\beta$ vs. position y',
b) Animation of a) for 1 period of oscillation, **c)** SW amplitude vs. wavevector **k**, **d)** Ellipticity of magnetisation at y=40nm.

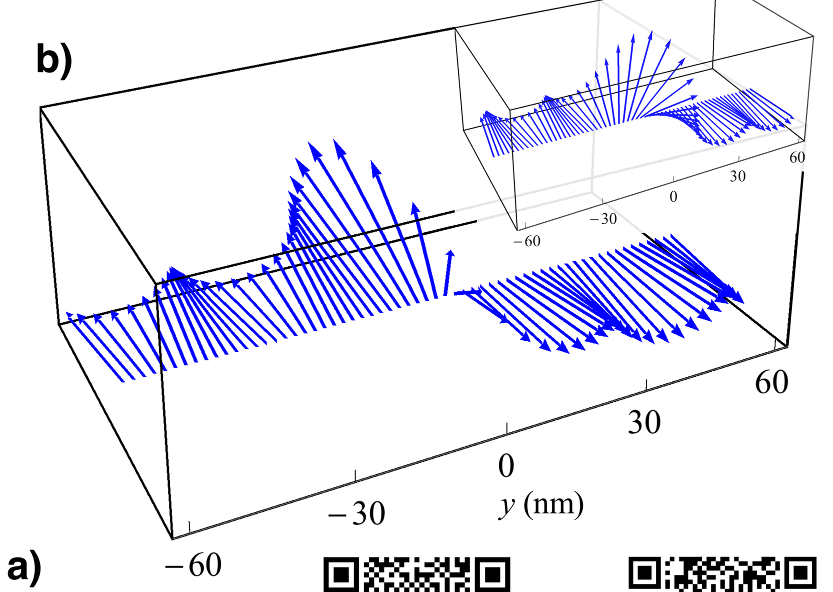
*Values used: α=3.125×10⁻¹²cm², γ=1.8×10⁷(Oe·s)⁻¹, M₀=800emu·cm⁻³, |**h**(t)|=1Oe, $\beta_\parallel$=0.1, $\beta_\perp$=10, frequency=$\omega/2\pi$=50GHz.*

- SWs are **elliptical** (Fig.4d) with ellipticity reducing at large **k**.
- Magnetisation vectors clearly show **SW emission** (Fig.5).
- Emission due to a **linear theory,** not a non-linear excitation of domain wall. **Full details in ref. [7].**

a)



b)



c) d)

Fig.5
Magnetisation vectors in unprimed frame, with **a)** axonometric view and **b)** side view, both for (main) phase = 0 and (inset) phase = π. **c)** animation of a), and **d)** animation of b), both with phase varying from 0 to 2π.

References

[1] V. V. Kruglyak, S. O. Demokritov, and D. Grundler, J. Phys. D: Appl. Phys. 43 264001 (2010).
[2] A. V. Chumak, V. I. Vasyuchka, A. A. Serga and B. Hillebrands, *Nat. Phys.* **11** 453-461 (2015).
[3] V. Sluka *et al.*, INTERMAG IEEE Abstract DE-03 (2015).
[4] B. Mozooni and J. McCord, Appl. Phys. Lett. **107** 042402 (2015).
[5] B. Van de Wiele, S. J. Hämäläinen, P. Baláž, F. Montoncello and S. van Dijken, Sci. Rep. **6** 21330 (2016).
[6] X. S. Wang and X. R. Wang, Phys. Rev. B **90**, 184415 (2014).
[7] N. J. Whitehead, S. A. R. Horsley, T. G. Philbin, A. N. Kuchko, V. V. Kruglyak, Phys. Rev. B. (in press) (2017)

nw276@exeter.ac.uk
ex.ac.uk/nw276
www.exeter.ac.uk/metamaterials

This research has received funding from the European Union's Horizon 2020 research and innovation program under Marie Skłodowska-Curie Grant Agreement No. 644348 (MagIC).

EPSRC
Pioneering research and skills